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著者	Hamaguchi Hiroyuki, Ndontoni Zana
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A Great Circle Distribution of Four Active Hotspots : Evidence for Deep Mantle Plumes

HIROYUKI HAMAGUCHI

Observation Center for Prediction of Earthquakes and Volcanic Eruptions,
Faculty of Science, Tohoku University, Aoba-ku, Sendai 980

NDONTONI ZANA

Département de Géophysique, Centre de Recherche en Sciences
Naturelles (C.R.S.N), D/S Bukavu, Rép. du Zaïre

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Abstract : This paper concerns a pattern of hotspots and mantle plumes in the lower mantle. Four hotspot volcanoes with presently vigorous activities, namely Hawaii, Iceland, Nyiragongo/ Nyamuragira and Mt. Erebus, are located at a regular interval of approximately 90 degrees on a great circle crossing closely the geomagnetic poles. This great circle is named "HINEP" in this paper. On this cross section, the three dimensional P velocity heterogeneity in the lower mantle shows a symmetrical pattern with respect to the axis connecting the geomagnetic poles. Manifestation of a plume-like pattern of the P velocity heterogeneity is recognizable in this cross section at the depth range from 1,000 km to the core-mantle boundary beneath the Hawaii, Nyiragongo/Nyamuragira and Iceland hotspots. Base heating from the core is a possible major contribution to the symmetrical pattern in the lower mantle, mantle plumes and consequent surface hotspots.

1. Introduction

Persistent lava lake activity is a special type of eruption at an open vent. Halemaumau crater at Kilauea volcano, which has been believed to be located on a fixed hotspot (Wilson, 1963, 1965 ; Morgan, 1971, 1972), is famous for the long-continued lava lake activity for a century. Records of eruptions in the world during historic (Macdonald, 1972) and recent times (BVE, 1961-1983) indicate that presently active volcanoes with a continuous or intermittent long-lived lava lake activity are strictly limited to the following places on the earth's surface ; Kilauea volcano in Hawaii, Nyiragongo/ Nyamuragira volcanoes in the western branch of the East African Rift Valley, Erta Ale volcano in Ethiopia and Mt. Erebus volcano in Ross Island, Antarctica. All of which are known as sites of typical intraplate volcanism.

Except the volcanoes that relate to the converging plate margins, recent eruptive activities have been mainly concentrated into the above volcanoes, and the volcanoes Piton de La Fournaise in the Indian Ocean and Iceland. The reported numbers of eruptions in the period from 1971 to 1981 are 8 in Hawaii, 12 in Nyiragongo and Nyamuragira, 5 in Erta Ale, 10 in Mt. Erebus, 8 in Piton de La Fournaise and 12 in

Iceland (BVE, 1971-1981). The frequency of eruptions does not directly reflect the energy release rate in the volcanic process. These simple figure of the eruptions, however, can be considered representative of the scale of the volcanic activity for the intraplate volcanism.

The Hawaiian volcanoes are among the best studied volcanoes in the world. Although several hypotheses have been proposed for the origin of Hawaiian hotspot, it remains unknown why the Hawaiian volcanism is located in the middle of the Pacific plate (Clague and Dalrymple, 1987). It also remains to be emphasized that we know nothing about the cause of the lava lake activities at the specially fixed volcanoes. Inside the African continent, the volcanoes Nyiragongo and Nyamuragira have had permanent lava lakes in the periods from 1928 to 1977 and from 1921 to 1938, respectively, and have been still in very active stages, notwithstanding that these volcanoes are located in the Congo craton that have been stable since the end of the Kibaran orogenesis ($1{,}100 \pm 200$ Ma) (Clifford, 1970). It is important to understand why the permanent lava lakes have been established in the middle of the African continent having a thick lithosphere.

In this paper, we briefly introduce the volcanoes Nyiragongo and Nyamuragira in the western branch of the East African Rift System, because these volcanoes are not well described in standard textbooks of volcanology (*e.g.* Bullard, 1984 ; Decker and Decker, 1981). Second, we show that four hotspot volcanoes with the present-day eruptive activity, namely Hawaii, Nyiragongo/Nyamuragira, Mt. Erebus and Iceland, are not randomly scattered over the earth's surface but are aligned on a great circle with the spacing of approximately 90 degrees. Third, we show the axisymmetrical distribution of the P velocity heterogeneity in the lower mantle on the cross section corresponding to the distribution of four hotspots. Fourth, we discuss the implications of the low-degree symmetrical pattern of four vigorous hotspots and the lower mantle heterogeneity as a direct evidence favouring the deep mantle plume rising from the core-mantle boundary.

2. Nyiragongo and Nyamuragira Volcanoes

The western rift valley, which is a part of the East African Rift System, is cutting into uplifted structures of the Precambrian basement and has deep lakes such as, from south to north, Malawi (472 m above sea level), Rukwa (782 m), Tanganyika (771 m), Kivu (1,463 m), Amin (Edward, 912 m) and Mobutu (Albert, 619 m). Lake Kivu is the highest lake in the western rift valley, implying that the center of doming accompanying the rift formation must be located around this lake. The Virunga volcano group, which is located at the northern edge of Lake Kivu, consists of three subgroups of eight major volcanoes ; the eastern (Muhavura (4,127 m), Gahinga (3,474 m) and Sabinyo (3,647 m)), the central (Visoke (3,911 m), Karishimbi (4,506 m) and Mikeno (4,437 m)) and the western (Nyiragongo (3,470 m) and Nyamuragira (3,056 m)) subgroups (Fig. 1).

The volcanoes in the western subgroup have been in the most active stage since the first decade of this century. Nyiragongo had a lava lake in the summit crater in the period from 1928 to 1977, which was renewed on June 21, 1982 (Hamaguchi and Zana,

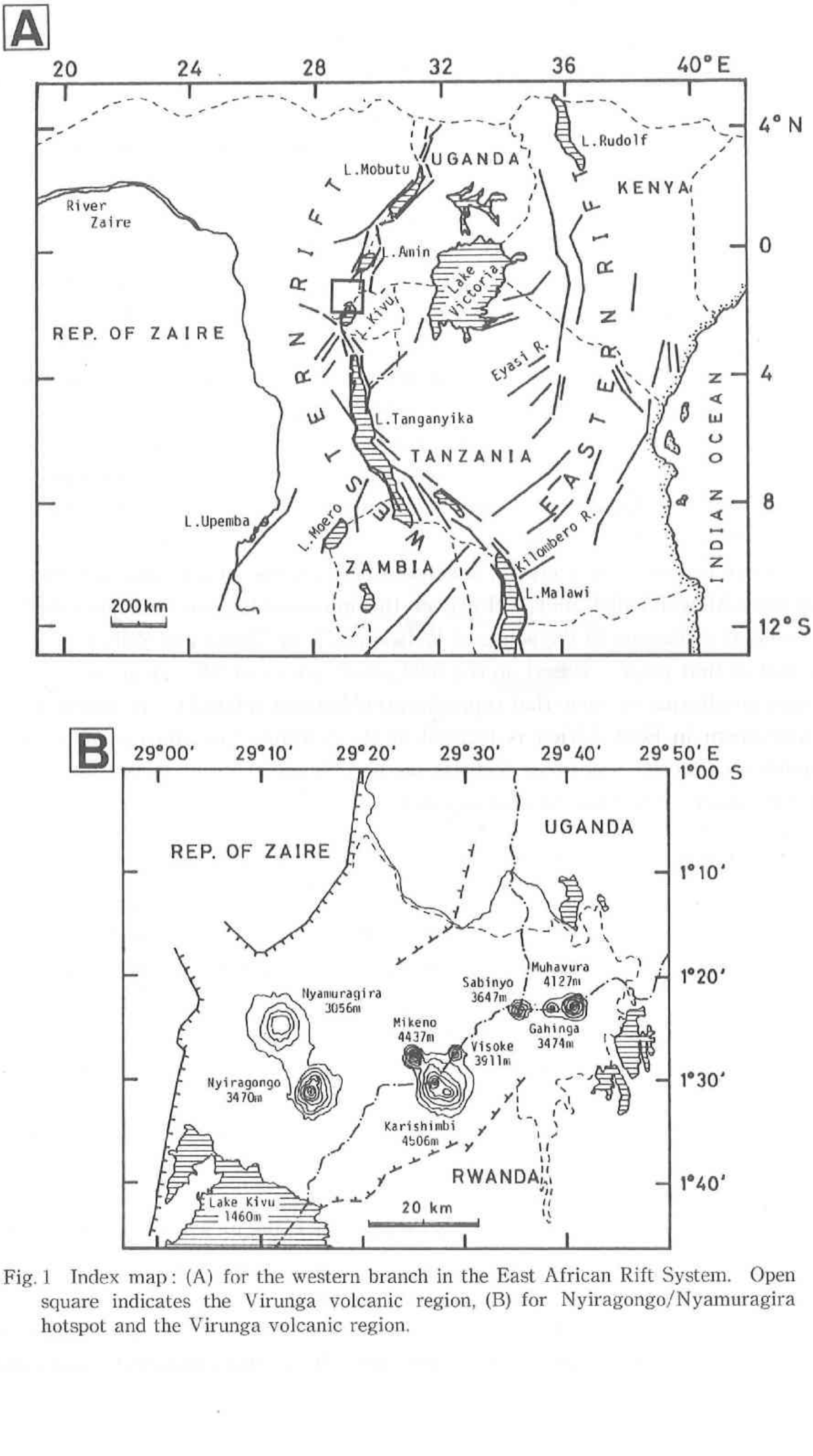

Fig. 1 Index map: (A) for the western branch in the East African Rift System. Open square indicates the Virunga volcanic region, (B) for Nyiragongo/Nyamuragira hotspot and the Virunga volcanic region.

1983). Lava lake activity is interpreted as a special variety of long-continued eruption at an open vent with a high magma level (Macdonald, 1972). On the other hand, Nyamuragira which is located at a distance of only 13 km northwest from Nyiragongo has two types of eruptive activity. One is a lava lake activity in the summit caldera (2 km in diameter) in the period from 1921 to 1938, and the other is a flank eruption issued from the opening of new fissures, which usually begins with lava fountains along the fissures and gradually converges into one place forming a cinder cone. The eruptions of the latter type were recorded 14 times since 1900 (Ueki, 1983).

Our recent geophysical studies on these volcanoes (Hamaguchi and Zana, 1983) revealed that these two volcanoes are among the most active intraplate volcanoes in the world. Some major element compositions of lava from the two volcanoes are slightly different, but the volcanic rocks are characterized by the alkali-rich basalt with highly potassic contents (Sahama, 1968, 1973; Aoki *et al.*, 1985) and are considered to be of mantle origin without significant crustal mixture (Aoki *et al.*, 1985). There is little doubt that the two active volcanoes embody all features of hotspot definied by Wilson (1973) or by Burke and Wilson (1976). The hotspot related to the topographic swell and recent rifting in East Africa was tentatively located by Morgan (1981) at somewhere near the southern end of Lake Victoria, which lies between the eastern and western branches of the East African Rift Valley. However, this inference has not been confirmed because any isolated volcanism in the sense of Wilson (1973) or Burke and Wilson (1976) cannot be found at that place. Based on the field observations of the volcanoes in Africa, we advance an alternative view that representative hotspot related to the recent rifting and the volcanism in East Africa is located at the Virunga volcano group including the presently most active volcanoes Nyiragongo and Nyamuragira. Hereafter, this hotspot is provisionally named the Nyiragongo hotspot.

3. Symmetrical Distribution of Four Active Hotspots

We suggest that the spatial distribution of the three active hotspot volcanoes with lava lake activity, namely Kilauea in Hawaii (**H**), Nyiragongo (**N**) in East Africa and Mt. Erebus (**E**) in Antarctica, provides an important clue concernig not only the reasons for their existences in the middle of each plate but also the origin of hotspot. Figure 2 shows the aligned distribution of the three hotspots and another large hotspot, Iceland (**I**), which is mapped on the azimuthal equidistance projection centered on the equator at 20°E longitude showing world seismicity 1963-1973 (Spilhaus, 1975).

The most striking spatial features of these hotspots are summarized as follows; (1) Four hotspot volcanoes are aligned on a great circle. (2) The great circle distances between Hawaii and Nyiragongo and between Iceland and Mt. Erebus are 162 and 168 degrees, respectively, suggesting that these pairs of hotspots are nearly antipodes. The former pair is located near the equator, while the latter is located near the polar region. (3) This great circle intersects closely the present geomagnetic poles (**P**), which are located at 78.8°N and 70.9°W in northwest Greenland, and 78.8°S and 109.1°E in Antarctica (Dawson and Newitt, 1982). Hereafter, we will call this great circle, connecting the

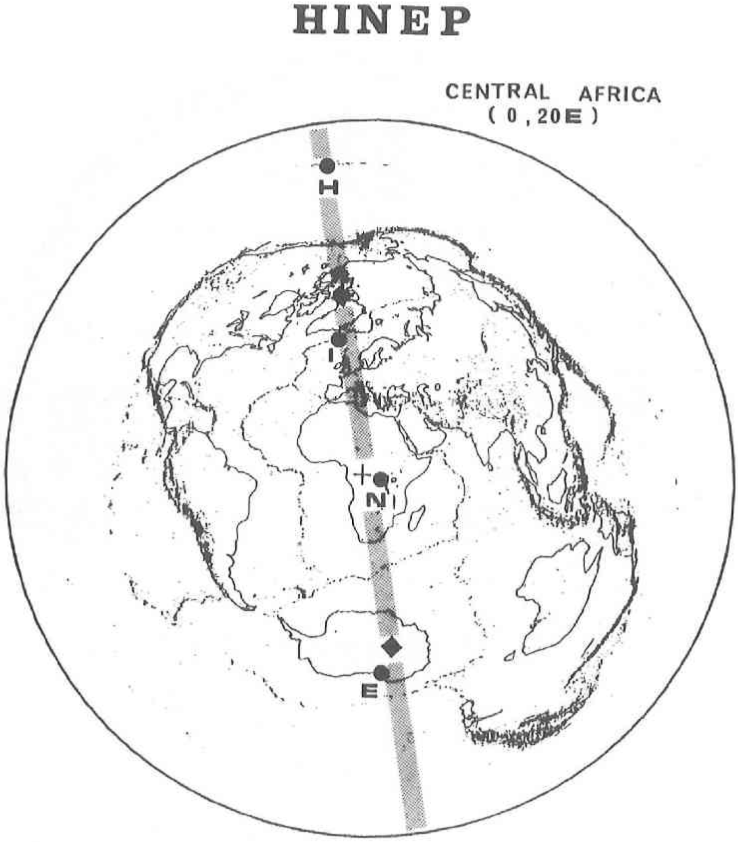

Fig. 2 Geographic map showing the HINEP great circle configuration of four specific hotspots (solid circle), Hawaii (**H**), Nyiragongo/Nyamuragira (**N**), Iceland (**I**), Mt. Erebus (**E**) and the geomagnetic poles (solid diamond). Two antipodal pairs of **H** and **N** and of **I** and **E** are noticeable. Map is the azimuthal equidistance projection centered on (0°, 20°E) showing the world seismicity of 1963–1973 (Spilhaus, 1975).

first letter of four hotspots and the geomagnetic poles, as the "**HINEP**" great circle.

This conspicuous degree of antipodal distribution of four hotspots on the HINEP great circle is attributed not to a mere chance of surface manifestation but to an intrinsic origin deep seated in the earth's interior. In the following section, we will discuss this low-degree geometrical symmetry of the active hotspots on the earth's surface with reference to the direct evidence for the deep mantle plumes, whose formation remains controversial.

4. Symmetrical Pattern in the Lower Mantle

To illustrate essential features related to the symmetrical distribution of hotspots on the HINEP great circle, we use a mapping of the global-scale three dimensional P velocity heterogeneity in the lower mantle given by Dziewonski (1984). He gave the solution (model L02.56) in the form of the spherical harmonics of a degree 6 and an order 6.

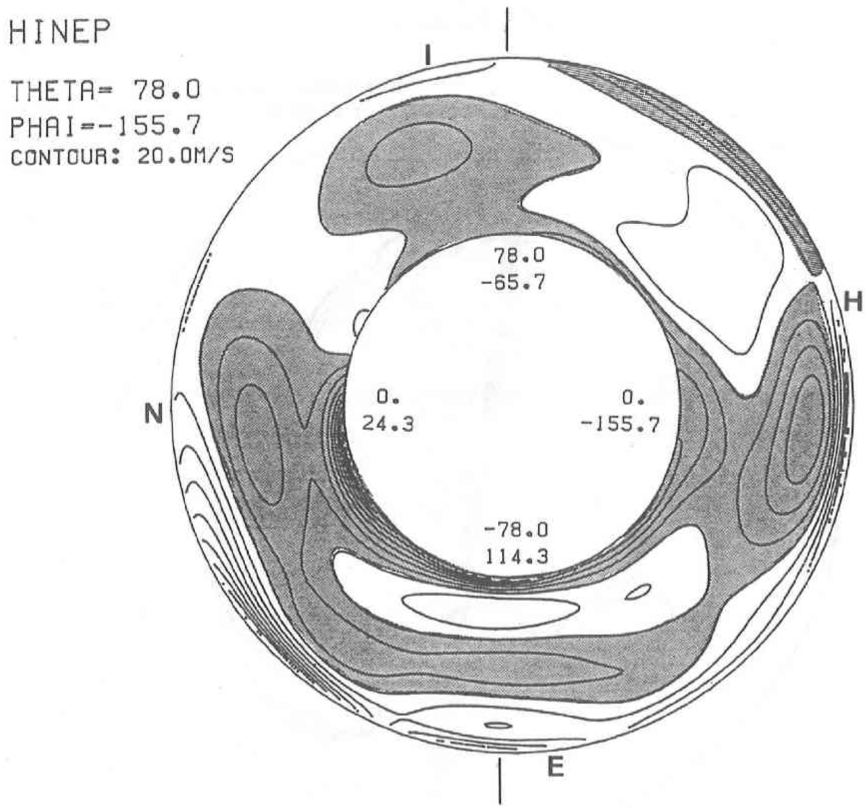

Fig. 3 Map of P velocity heterogeneity in the lower mantle projected on the cross section corresponding to the HINEP great circle. This is synthesized using the coefficients of the model L02.56 by Dziewonski (1984). Contour interval is 20 m/s. The shaded area indicates slow velocity perturbations. The symmetrical pattern with respect to the axis connecting the geomagnetic poles and three plume-like patterns beneath the Hawaii (**H**), Iceland (**I**), and Nyiragongo (**N**) hotspots are the most important features. No plume-like pattern is found beneath the Mt. Erebus (**E**) hotspot. The upper and lower radii correspond to 670 km and 2,891 km, respectively. The numerals within circle indicate latitude and longitude at which the HINEP crosses the equator and highest latitudes reached by the great circle.

Using the coefficients for this model, we synthesized the pattern of heterogeneity of P velocity on the cross section corresponding the HINEP great circle (Figs. 3 and 4): The upper and lower radii of the cross section correspond to 670 km discontinuity and the core-mantle boundary (2,891 km), respectively. The numerals within circle indicate latitudes and longitudes at which the HINEP great circle crosses the equator and the highest latitudes reached by the circle. These figures illustrate, on a global scale, the almost perfect symmetrical pattern of the P velocity heterogeneity with respect to the axis connecting the present geomagnetic poles, which inclines at aboout 12 degrees to the axis of earth's rotation. Our syntheses for various cross sections reveal that the axisymmetrical pattern appears on only this cross section corresponding to the HINEP

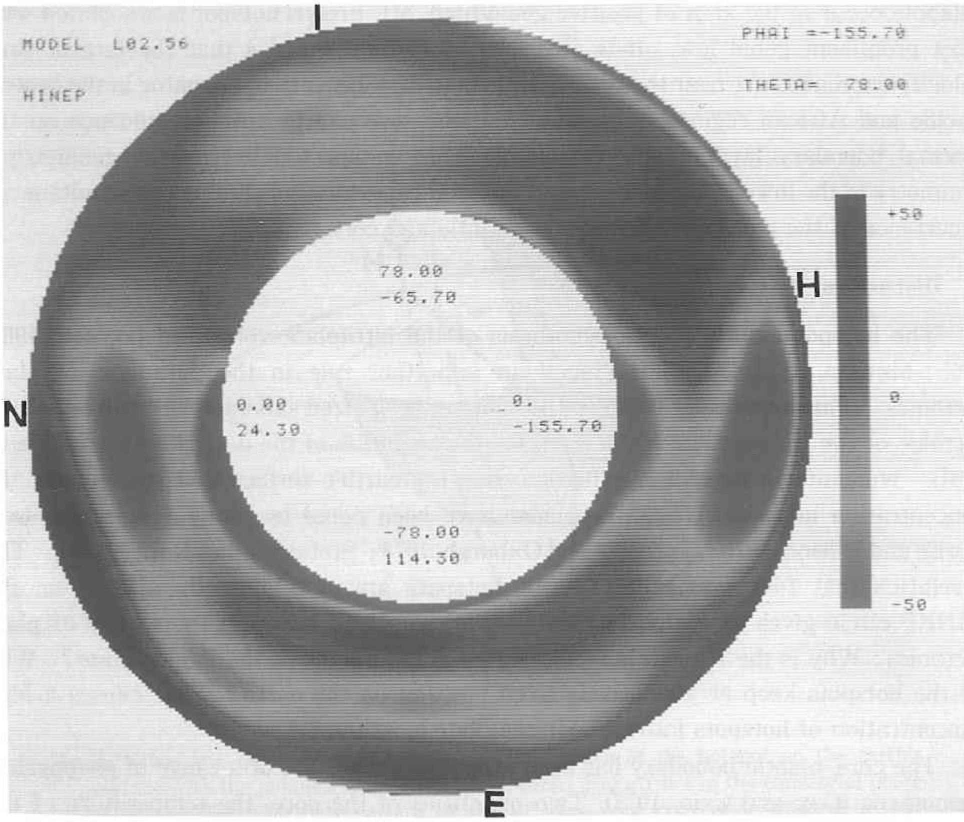

Fig. 4 Map of P velocity heterogeneity in the lower mantle projected on the cross section of the HINEP great circle (see Fig. 3 and text for a full description). Scale on the color bar is in meter/second. Anomalies exceeding the scale range are clipped at the maximum absolute values.

great circle. This is the most important features encouraging a causal relation between the pattern of the active hotspts on the earth's surface and the P velocity heterogeneiy in the lower mantle.

An additional spectacular feature in these figures is that the three plume-like patterns of slow velocity anomalies in the depth range from 1,000 km to the core-mantle boundary (2,891 km) are perceived beneath the Hawaii (**H**), Nyiragongo (**N**) and Iceland (**I**) hotspots, which are the most active volcanoes on our planet Earth. This figure is the first visualization of the pattern of mantle plume originating at the core-mantle boundary, which has been suggested by Morgan (1971, 1972) as an origin of surface hotspots such as Hawaii and Iceland. The configuration of four hotspots on the HINEP great circle can be explained by mantle plumes bringing up heat and relatively primordial material from the core-mantle boundary. The exceptional case among four hotspots is Mt. Erebus in Antarctica, under which no distinct plume-like pattern is observed (Figs. 3 and 4). This circumstance is perhaps connected with the fact that, though most hotspots occur in the area of positive geoid high, Mt. Erebus hotspot is associated with most prominent geoid low. It is also noticed in Figs. 3 and 4 that the largest slow velocity anomalies are near the core-mantle boundary beneath the equator in the central Pacific and African regions, suggesting that the core exerts a major influence on the thermal boundary layer of the D″ layer. This unexpected low-degree geometrical symmetry in the lower mantle leads to a new and basic idea concerning the simultaneous occurrence of the convective motions in mantle and core.

5. Discussion

The hotspot-mantle plume hypothesis of the intraplate volcanism (Wilson, 1963, 1965; Morgan, 1971, 1972) has played an important role in the paradigm of plate tectonics. This hypothesis, however, has not yet been fitted satisfactorily into either the tectonic or the geochemical framework for the evolution of the deep mantle (Anderson, 1981). Nonuniform hotspot distribution over the earth's surface and particularly the concentration into the African continent have been noted by many researchers (*e.g.* Burke and Wilson, 1976; Turcotte and Oxburgh, 1978; Stefanick and Jurdy, 1984). The revelation that four presently vigorous hotspots are systematically aligned on the HINEP circle gives us a clue to the following unsolved issues in the theory of plate tectonics: Why is the Hawaii hotspot located in the middle of the Pacific plate? Why do the hotspots keep at a relatively fixed position on the earth? What causes a high concentration of hotspots into the African plate?

The core-mantle boundary has been proposed as the seat of a range of geophysical phenomena (Cox and Cain, 1972). Two quantities of the core, the temperature of the core-mantle boundary and the amount of heat flowing out from the core, are important boundary conditions for the mantle dynamics (Elsasser *et al.*, 1976). The possibility of hotspots and coldspots on the core-mantle interface was originally suggested as the result of geomagnetic observations (Cox and Doell, 1964; Doell and Cox, 1972). They gave a possible explanation to the large virtual geomagnetic poles (VGP) excursion that the excitation of such geomagnetic signals in the earth's core may be partially controlled by lateral variations in the physical properties of the lower mantle or by undulations in the core-mantle boundary.

We inferred that a low degree axisymmetrical pattern in the lower mantle and consequent antipodal distribution of the hotspots on the earth's surface resulted fundamentally from the cause symmetry in the earth's core. The core convection expected by the self-exciting dynamo model (Bullard, 1972) is the most compatible source for the symmetrized pattern. An essential feature of the dynamo theory of Bullard and Gellman (1954) is that the fluid motion in the earth's core possesses the first-order symmetry with respect to the earth's axis of rotation. The pattern of the convection of type S_2^{2c} in the dynamo model is one in which material rises near the two ends of a diameter in the equatorial plane, fans out on approaching the surface of the core and descends near a diameter 90 degrees different in longitude from the first. If the upwelling flows of the thermally driven poloidal type convection does exist in the core, they

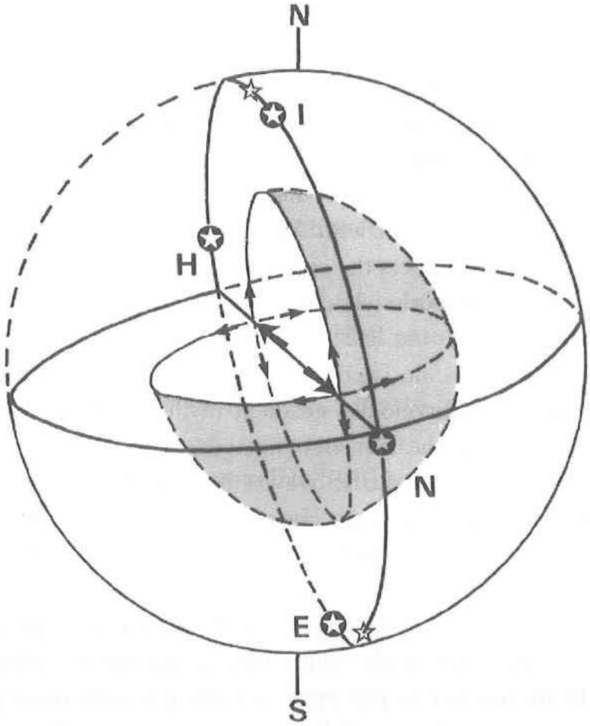

Fig. 5 Schematic representation for the correspondence of the hotspot on the earth's surface with the poloidal convection in the core. Big arrows in the equatorial plane show the upwelling flow pattern of the S_2^{2c} type core convection inferred in the kinematic dynamo model. The letters **H**, **I**, **N** and **E** indicate the Hawaii, Iceland, Nyiragongo and Mt. Erebus hotspots, respectively. The geomagnetic pole positions are shown by open stars.

make a significant contribution to the flux of heat across the equator of the core-mantle boundary and thereby perhaps infuluence the mantle convection. Figure 5 shows a schematic presentation of the S_2^{2c} type convection in the core and the four active hotspots on the HINEP great circle. The rising columns in the core are indefinite longitudinally, but if the column is tentatively fixed beneath Nyiragongo (N) hotspot, then the other does nearly correspond with Hawaiian (H) hotspot. An axisymmetrical pattern of two plumes at the equatorial region in the lower mantle is attributable to the following mechanism occurring in the core-mantle boundary ; (1) a local reduction in viscosity on the equator of the core-mantle boundary will result from the base heating at the two upwelling points in the core (source of S_2^{2c} movement), because of a strongly temperature dependent viscosity in the lower mantle (Yuen and Peltier, 1980a), and (2) an ejection of thermal plumes should occur as a cosequence of buoyancy instability (Howard, 1966 ; Yuen and Peltier 1980b ; Spohn and Schubert, 1982).

Sacks and his co-workers (Carnegie Institute, 1984) believed that the inhomogeneities in the lower most mantle are most likely produced by uneven heat flow across the core-mantle boundary and that convection in the core could be related to convection in the mantle. It should be noted, however, that the difference between Sacks' and our inferences is whether there are any geometrical specifications of the uneven heat points at the core-mantle boundary and of a consequent configuration of mantle plumes causing the hotspot volcanoes on the great circle of the earth's surface.

The present inference that the convection in the mantle does primarily respond to the current in the core is inconsistent with Anderson's (1981) conclusion that the convection in the mantle presumably affects the convection in the core. This different view for how the interior of the earth works should be examined by various branches of earth sciences.

Without carrying these speculative discussions any further, we should like to remark the lateral heterogeneity of the velocity gradient in the D″ layer and the bump of the core-mantle boundary beneath the Hawaiian hotspot. Based on the seismic analyses of the travel times between SKKS and SKS waves, Morita (1987) revealed that a bump of the core-mantle boundary exists beneath Hawaii and that the height and lateral dimension of the bump are about 10 km and a thousand kilometers, respectively. He also showed that the velocity gradients in the D″ layer are laterally varied. The velocity gradient of the D″ layer in the north-western region of the Hawaii Islands is negative (-20×10^{-4} sec^{-1}), whereas that in the south-eastern region is positive (5×10^{-4} sec^{-1}). The former value is interpreted by the super-adiabatic temperature gradient in the D″ layer and the latter one is nearly an adiabatic temperature gradient. The bump on the core-mantle boundary and the development of the thermal boundary layer in the D″ region beneath Hawaii is presumably caused by the excess heat flow from the core.

In summary, the present study has clarified that the location of the Hawaii and Nyiragongo hotspots correlates intimately with the degree two geometrical symmetry of the convection currents in the mantle and core, and that the origin of the Hawaii and Nyiragongo hotspots is setteled on the core-mantle boundary. The axisymmetry of the P velocity heterogeneity in the lower mantle and distribution of the four hotspots along the HINEP great circle on the earth's surface give the observational basis for the Morgan's (1971, 1972) mantle plume hypothesis.

6. Conclusions

The conclusions reached in this paper are summarized as follows:

(1) Volcanoes Nyiragongo and Nyamuragira that belong to the Virunga volcano group in the western branch of the East African Rift System are representative continental hotspots in the African plate, though these two volcanoes have been disregarded in recent hotspot catalogues.

(2) The presently active three hotspot volcanoes having a long-continued lava lake activity in their craters, namely Hawaii, Nyiragongo/Nyamuragira and Mt. Erebus, and the Iceland hotspot having the Greenland-Faeroe Plateau, are aligned on the HINEP great circle crossing the nearby geomagnetic poles.

(3) A pattern of the P velocity heterogeneity in the lower mantle on the cross

section corresponding to the HINEP great circle shows almost perfect axisymmetry with respect to the axis connecting the geomagnetic poles.

(4) The antipodal orientation of hotspots on the HINEP great circle and the low-degree geometrical axisymmetry in the lower mantle are primary observational basis for the existence of plumes and for the hotspot fixity to the earth's axis of rotation. The global symmetries of the hotspot distribution on the earth's surface and of the earth's interior might provide the important information for solving the problem of the evolution of the earth.

(5) The base heating from thermally driven poloidal core convection (S_2^{2c} type) is presumably driving force for the axisymmmetrical pattern in the mantle.

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